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OXYGEN-JET BEHAVIOR DURING COMBUSTION INSTABILITY
IN A TWO-DIMENSIONAL COMBUSTOR

By M. F. Heidmann

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IN A TWO-DIMENSIONAL COMBUSTOR

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ABSTRACT

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A burning liquid-oxygen jet was observed photographically during both stable and unstable operation in a gaseous-hydrogen-fueled rocket combustor. The stable jet appeared as a loosely contained mass of liquid, which disintegrated into a maze of interconnected ligaments. Normal drop formation was not observed. During chugging instability, the oxygen flow rate responded to chamber-pressure oscillations and caused large variations in the atomization process. The burning rate appeared to respond to both the degree of atomization and the quantity of liquid within the combustor. Cyclic variations in the magnitude and the position of the primary burning zone were evident. With high-frequency transverse instability the length of the burning jet decreased from its stable value and responded to the oscillations. No abrupt change in jet characteristics were evident during the cyclic process. Mass removal appeared as a continuous process depending on gas velocity and the amount of liquid subjected to this velocity.

AUTHOR

INTRODUCTION

The atomization and burning of noncryogenic liquids have been extensively studied in a variety of environments. A basic understanding has evolved which, for many conditions, adequately describes the combustion process. A similar knowledge about liquid oxygen and other cryogenic liquids does not exist. Nonburning studies of the atomization process of liquid oxygen are incomplete. Extrapolation of results for noncryogenic liquids to liquid oxygen may be inadequate because of large and uncertain differences in the physical properties. One of the purposes of this study was to obtain a general physical description of a burning liquid-oxygen jet during stable combustion to define unique characteristics requiring more extensive study.

With regard to unstable combustion, the injection and atomization processes are only partially understood for all liquids. The dynamic behavior of injection processes has been studied in shock tubes, resonant cavities, pulsed liquid flow systems, and other devices which produce unstable combustor conditions. Substantial effects on the atomization process have been observed, and a degree of understanding is evolving. Most of the experimental techniques involve nonburning sprays. The dynamic behavior in a burning spray is

is more complicated because mass is continually being removed by vaporization, mixing, and chemical reaction. This mass removal process can also respond to rapidly changing environmental conditions. The net effect of periodicity in the injection process with periodicity in the combustion or mass removal process remains to be evaluated. Its importance is implied in an instability analysis being conducted by R. J. Priem at the Lewis Research Center. A relation is evident between the liquid mass within the combustor and the growth of a disturbance. The net amount of mass, the degree of cyclic variation in this liquid mass, and the phase relation to the disturbance may provide a criteria for stability. The analysis is for screaming instability; however, liquid mass within the combustor may be equally important for chugging instability. A primary purpose of this study was to observe an injection and combustion process during instability to confirm the existence of cyclic variations in atomization and other phenomena predicted from nonburning and theoretical studies.

The studies reported herein were made in a two-dimensional combustor that permitted detailed observations of the injection and burning process. Observations were made in the stable, chugging, and spinning transverse instability regions. Liquid-oxygen jets in a diffuse hydrogen atmosphere formed the basic injection and combustion pattern.

EXPERIMENTAL TECHNIQUE

A two-dimensional circular combustor (fig. 1) was used. The combustor basically consists of a circular injector ring 8 inches in diameter and 1/2 inch thick with 48 oxygen jets, which inject radially toward the center of the ring. (Hydrogen is introduced in a diffuse manner near the oxygen jets.) Both sides of the ring are covered with circular plates, one solid and the other with an exhaust port at its center. The 48 oxygen jets are 0.023 inch in diameter and are equally spaced around the circumference. Jet behavior was observed through 1-inch-diameter windows, which were centered on an individual oxygen jet.

Combustion tests were made with a pressurized liquid-oxygen tank and flow system that was cooled to liquid-nitrogen temperatures. A pressure-regulated gaseous-hydrogen supply system at ambient temperatures was used. Combustion pressure and oxygen and hydrogen flow rates were the primary parameter measurements for steady-state performance. A Kistler-type 601 pickup and detection system with a water-cooled holder was used for dynamic pressure measurements. The transducer was located immediately adjacent to the window to detect dynamic pressure conditions at the region of observation.

Transverse combustion instability was induced by tangentially injecting nitrogen gas through a 1/8-inch-diameter port into the combustor. The injection port was near the circumference of the combustor. Nitrogen flow rates of 0.029, 0.055, 0.112, and 0.222 pound per second were used to vary the degree of instability. The flow rate was established by interchangeable critical-flow orifice restrictors located in the flow line 10 orifice diameters upstream of the injection point. Nitrogen gas was injected for 0.3 to 0.4 second during a $1\frac{1}{2}$ -second test firing.

Instability was induced by this technique in a similar two-dimensional combustor described in NASA Lewis film C-226, which is available on loan.

(A request card is included at the back of this paper.) The film presents high-speed motion pictures of stable and unstable combustor operation as observed through a transparent top cover plate. Overall combustion and flow patterns are described for spinning transverse instability.

In this study high-speed motion pictures were taken through the 1-inch-diameter windows. A collimated light beam from a concentrated zirconium arc was passed through the combustor, and silhouette-type pictures were taken. Ektachrome ER type B color film was used. A cutoff filter placed between the light source and the combustor passed all light about 5800 Å. The camera recorded a silhouette of the oxygen jet against a red background with blue light from the hydrogen and oxygen reaction superimposed on this background.

COMBUSTOR PERFORMANCE

The combustor performance over the operating range covered in this study is shown in figures 2 and 3. Characteristic-velocity efficiency C^* varied from 75 to 90 percent, which indicated incomplete combustion, throughout the operating range when nitrogen gas was not injected to incite instability. Injection pressure drop (fig. 3) was high for hydrogen and low for oxygen. Oxygen pressure drop covered the range of interest in chugging instability, whereas hydrogen flow should have been relatively insensitive to chamber-pressure changes.

The burning oxygen jet for typical steady-state combustion is shown in figure 4. This is an enlargement of a single 16-millimeter frame of color film, which in a black-and-white print does not clearly show the burning zone. Analysis of such photographs shows that a luminous combustion zone uniformly enveloped the jet at the jet origin. The zone extended about 0.15 inch from the jet surface. The zone expanded and became turbulent downstream from the jet origin. The oxygen jet was loosely confined as compared to water or hydrocarbon jets. The appearance during breakup was that of a maze of interconnected ligaments. Isolated liquid particles were irregular in shape, and typical drop formation was not observed within the limit of resolution, about 100 to 200 microns.

A low surface tension is implied by the jet appearance. Surface tension varies with liquid-oxygen temperature. At the injection temperature it is less than but comparable to that of hydrocarbons. The temperature of the burning jet, however, is not known, and surface tension may be reduced to extremely low values if combustion heat is transferred to the oxygen. A high vaporization rate and the close proximity of the combustion zone may also affect surface properties. Additional studies appear necessary to prescribe oxygen atomization characteristics within the combustor.

CHUGGING INSTABILITY

Self-induced chugging instability developed over a major portion of the combustion operating range. Figure 5 shows several characteristics of this instability. The amplitude of the pressure oscillation is divided into four regions, with region 1 defined as stable. The parameter that approximates the boundary between these regions is $\Delta P_{ox}/P_c$ (presented in fig. 3). A stable condition exists with $\Delta P_{ox}/P_c$ greater than about 0.25.

Two modes of oscillation were encountered, a fundamental chugging mode and a mode with a frequency about 2.7 times the fundamental. This higher frequency condition occurred randomly and only in region 2. The mode has not been identified.

The four regions were separated on the basis of pressure amplitude; the primary reason for this division was the wave shape. The wave shapes are shown in figure 6. The most severe oscillations occurred in region 4, and a cusp-shaped wave, characteristic of nonlinear effects, was obtained. A change in operating conditions toward a region of stability caused progressive changes in wave shape. A sinusoidal wave was evident in region 3, the wave becoming steep-fronted in region 2 before stability was reached in region 1. An alternative condition in region 2 was a sinusoidal high frequency and a mixed-mode wave shape. Such a progression in wave shape suggests a shifting of phase relation between the driving, driven, and resonant parts of the system.

The oxygen-jet characteristics in the four regions are shown in figure 7. An extreme oscillation in flow rate is evident for region 4 with almost complete termination of flow during low flow conditions. A characteristic of such flow oscillations is the liquid mushroom that developed during flow acceleration. It was produced when high-velocity flow leaving the orifice impinged on lower velocity flow that had preceded it, and it caused a piling-up of oxygen. Flame radiation surrounded the liquid oxygen at all times. Its intensity oscillated depending on the amount of oxygen present and its degree of atomization or dispersion. The degree of atomization was obviously not constant. The injection and combustion process appears to have behaved nonlinearly, which may account for the shape of the pressure wave observed in this region.

Changes in liquid-jet characteristics were less severe in region 3 and became progressively more stable in region 2. In some instances the oscillation in flame radiation, not shown in the reproductions, was more evident than changes in atomization. Flame radiation changes, however, may indicate a combustion change caused by an oscillation in pressure or environmental conditions rather than atomization. The description of the oxygen jet in regions 2 and 3 is not complete because of the limited view through the observation ports. Downstream of the window the jet may have had properties similar to those observed in region 1. Jet behavior during higher mode oscillations were not isolated because of the random occurrence of this instability.

These observations indicate that the atomization of liquid oxygen during chugging may exhibit nonlinear behavior. This causes the combustion zone to oscillate in intensity and position. Such oscillations may be more severe for a combustion process controlled by oxygen injection and atomization than by injection and atomization of other liquids. The loosely bound property of oxygen jets and ligaments makes it particularly sensitive to perturbations in flow rate and combustor conditions.

SPINNING TRANSVERSE INSTABILITY

The modes of transverse instability induced by nitrogen flow are shown in figure 8. Sustained oscillations was the criteria separating stable and

unstable regions regardless of the wave amplitude. The boundaries separating stability regions are approximate and are primarily shown to indicate trends. The first transverse mode was identified as spinning by simultaneous observations at several positions in the combustor.

A comparison of the four stability maps in figure 8 shows the effect of nitrogen flow rate on inducing instability. As nitrogen flow rate increased, the unstable operating region expanded. The amplitude of the oscillation also increased and was approximately proportional to the increase in nitrogen flow. It is interesting to note that the third harmonic occurred prior to the second as the instability region expanded. Combined chugging and transverse instability occurred at low oxygen flow rates. The chugging region, however, was not as extensive as that when there was no nitrogen flow and generally exhibited an increase in frequency.

A circular flow was induced by the injection of nitrogen gas, which changed the normal burning process and produced conditions conducive to sustaining combustion instability. Several tests with hydrogen rather than nitrogen injection indicated that the momentum of the injected gas establishes the degree of instability. Inertia and other forces resisting circular flow would be assumed to be controlling parameters. A constant tangential flow rate would be most effective in inducing circular flow at low combustor pressures. The stability maps appear to reflect this condition, since low nitrogen flow rates induced instability at low pressures.

The frequency and pressure amplitude of the oscillation for the highest nitrogen flow condition are shown in figures 9 and 10. The frequencies compare very closely to that of a 100-percent-efficient combustor, although they were somewhat lower at lesser nitrogen flows. A direct comparison with performance efficiency was not made because combustor pressure was measured near the circumference and the added pressure drop due to circular or vortex flow increased the pressure needed for performance evaluations by an unknown amount. The amplitude shown in figure 10 is approximate because of uncertainties caused by wave shape and transducer response. A transducer calibration showed linearity of ± 10 percent for frequencies up to 10,000 cps, however.

As operating conditions were changed toward a region of stability, a progressive change in the wave shape of the pressure oscillations was observed. The general nature of the wave-shape progression is shown in figure 11, although additional variations were also detected. Wave-shape progression was somewhat similar to that observed with chugging instability, i.e., steep-fronted waves to higher modes to stable combustion. Again, a time response that affects amplitude, frequency, and wave shape of the oscillation is implied.

The progression observed in wave shape also implies that one form of stable combustion may result from a highly responsive process that drives an extremely high frequency at low amplitude. Pressure records in the stable region with high nitrogen flow contained high-frequency hash, whereas a smooth record existed without nitrogen flow. These two stable conditions may have been stable for distinct reasons. The theoretical analysis by Priem shows that stability can exist with low and extremely high burning rates; instability occurs at some intermediate burning rate. Stability with and

without nitrogen flow may be of these two types.

High-speed motion pictures of the jet during the transient from stable to unstable combustion are shown in figure 12(a). Cross velocity caused by the nitrogen flow accelerated the combustion process and reduced the length of the oxygen jet. Study of such photographs together with pressure records indicate that the nitrogen flow established a new level of combustion rate followed by the growth of an oscillation. The nitrogen flow established a condition conducive to instability rather than pulsing the combustor into an unstable condition.

The stable-to-unstable transition in a region of strong chugging instability differed in character, as shown in figure 12(b). Combustion pressure was increased by nitrogen addition and accelerated burning. Oxygen flow rate reacted to the pressure change and terminated for a short period of time. The oscillation persisted through a period when there was no burning.

Jet behavior during transverse instability of the first mode is shown in figure 13. These photographs time resolve jet behavior during wave motion by a stroboscopic effect. Successive photographs display conditions in successive oscillations. The photographs, however, were taken at an advancing phase relation with respect to the oscillation. One to two cycles are displayed by this technique in figure 13.

Figure 13(a) shows jet behavior during high-amplitude oscillations. Average jet length was about 1/4 inch. The jet length varied during the oscillation, however. Precise tracking of the jet length is difficult because of the stroboscopic technique. Jet characteristics were not precisely repeated for each cycle, and detail changes have not been time resolved. The varying jet length indicates that liquid mass within the combustor varied periodically, which agrees with analytical deductions obtained in reference 1.

Gas velocity appears to have caused the variations in jet length. The velocity effect was most pronounced at the leading edge of the jet. The effect was not abrupt. It appears to have persisted at varying degrees throughout the cycle. Loosely confined oxygen was displaced or stripped from the main body and rapidly disappeared because of vaporization and burning.

Figures 13(b) to (d) show jet behavior at progressively less severe oscillatory conditions. Average jet length increased, and the mass removal process became less severe. Shattering of the main bulk of the jet was not observed under any conditions. Shattering of ligaments may have occurred, however. Stripping of liquid from the main body appears as a more important factor than effects caused by internal excitation within the liquid.

SUMMARY OF RESULTS

A study of the behavior of liquid-oxygen jets in relation to combustor performance characteristics gave the following results:

With stable combustion, a loosely confined jet was formed, which disintegrated into a maze of interconnecting ligaments. Combustion radiation surrounded the jet and the ligaments. Normal drop formation was not observed.

Chugging instability was characterized by progressive changes in the wave shape, frequency, and amplitude of the pressure oscillations. The pressure oscillations caused pronounced changes in the oxygen flow rate and the degree of atomization. Combustion radiation varied in position and magnitude depending on the degree of atomization and the amount of liquid in the combustor. A complex interaction of parameters is implied.

Screaming instability, with a spinning transverse mode predominating, was induced by tangentially injected nitrogen gas. Wave shape, frequency, and amplitude of the pressure oscillations showed progressive changes that indicated a variable response time of interacting parameters. The average length of the oxygen jet decreased during screaming. The jet length varied periodically with the oscillation; however, no abrupt changes in atomization were observed. Oxygen appeared to be continuously stripped from the main bulk of the jet by the varying gas velocity that accompanied the oscillation. The process varied with the amplitude of the oscillation.

CONCLUDING REMARKS

A unique characteristic of the burning liquid-oxygen jets observed in this study was the loosely continued nature of the jet. A more quantitative evaluation of this jet structure and breakup process is needed before the steady-state burning process of liquid oxygen and hydrogen can be fully described. This jet property also appears to make the burning process particularly sensitive to flow rate and combustor environment changes encountered during combustion instability. Jet behavior during instability appears to be an important interacting process, as was anticipated from analytical studies. Only a general physical description of the behavior was obtained, whereas specific knowledge of changes in the atomization and mass-removal process is needed. The phase relation between jet behavior and various combustor parameters is also needed to proceed in the evaluation of analytical models of combustion instability. The ability to observe the behavior of the burning jet makes this combustor applicable to further studies of this type.

Place
stamp
here

Chief, Technical Information Division (5-5)
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

A 15 minute, 16mm, sound, color film (NASA Lewis film C-226) pertaining to a two-dimensional circular combustor of the type used in this study has been prepared. The film presents an animation of spinning transverse acoustical resonance and high speed motion pictures of the overall combustion process.

Lewis film C-226, entitled "Visualization Studies of Combustion Instability in a Hydrogen-Oxygen Model Combustor," is available on request from

Chief, Technical Information Division (5-5)
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

Date _____

Please send, on loan, Lewis film C-226

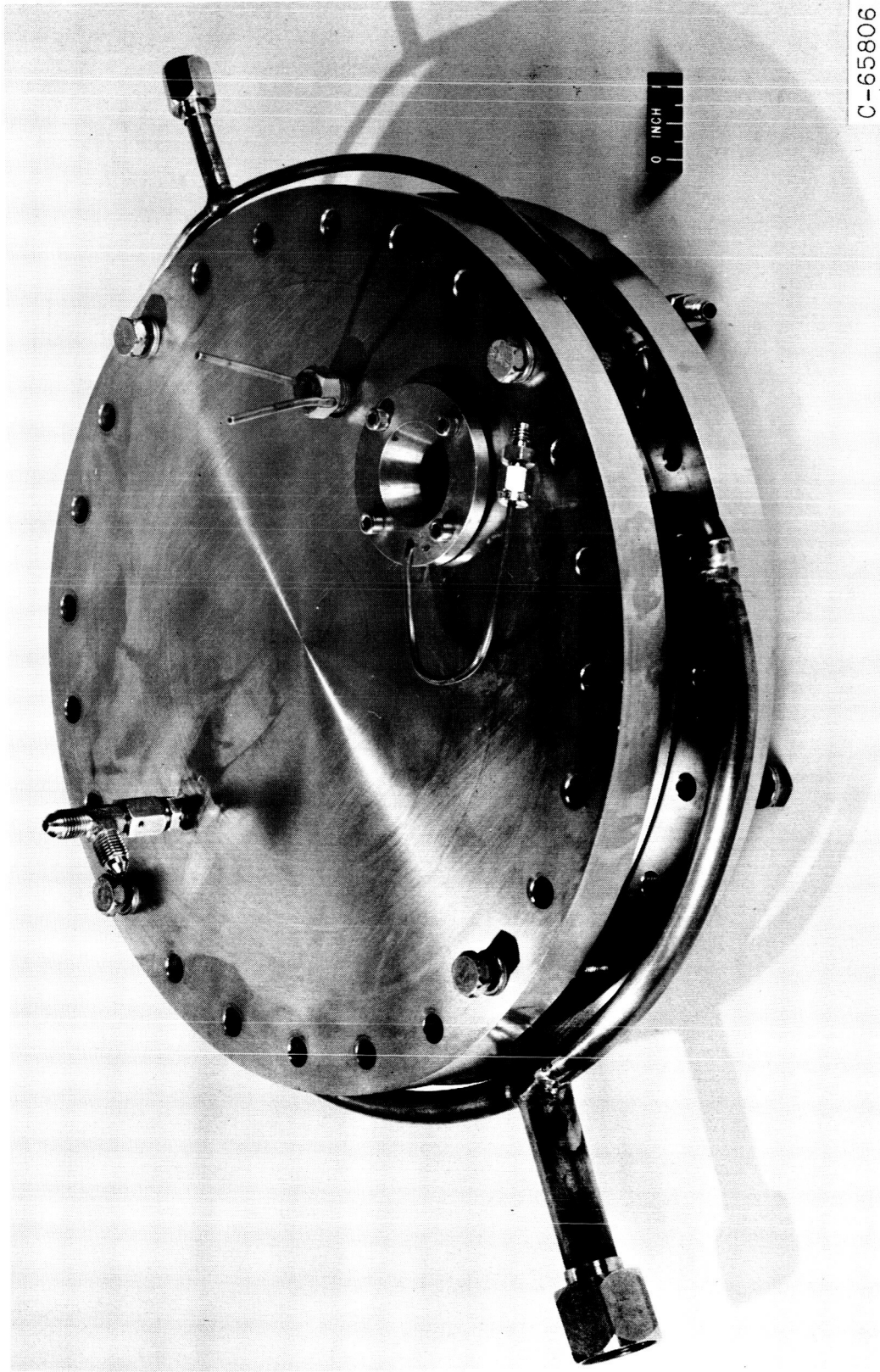
Name of organization

Street number

City and State

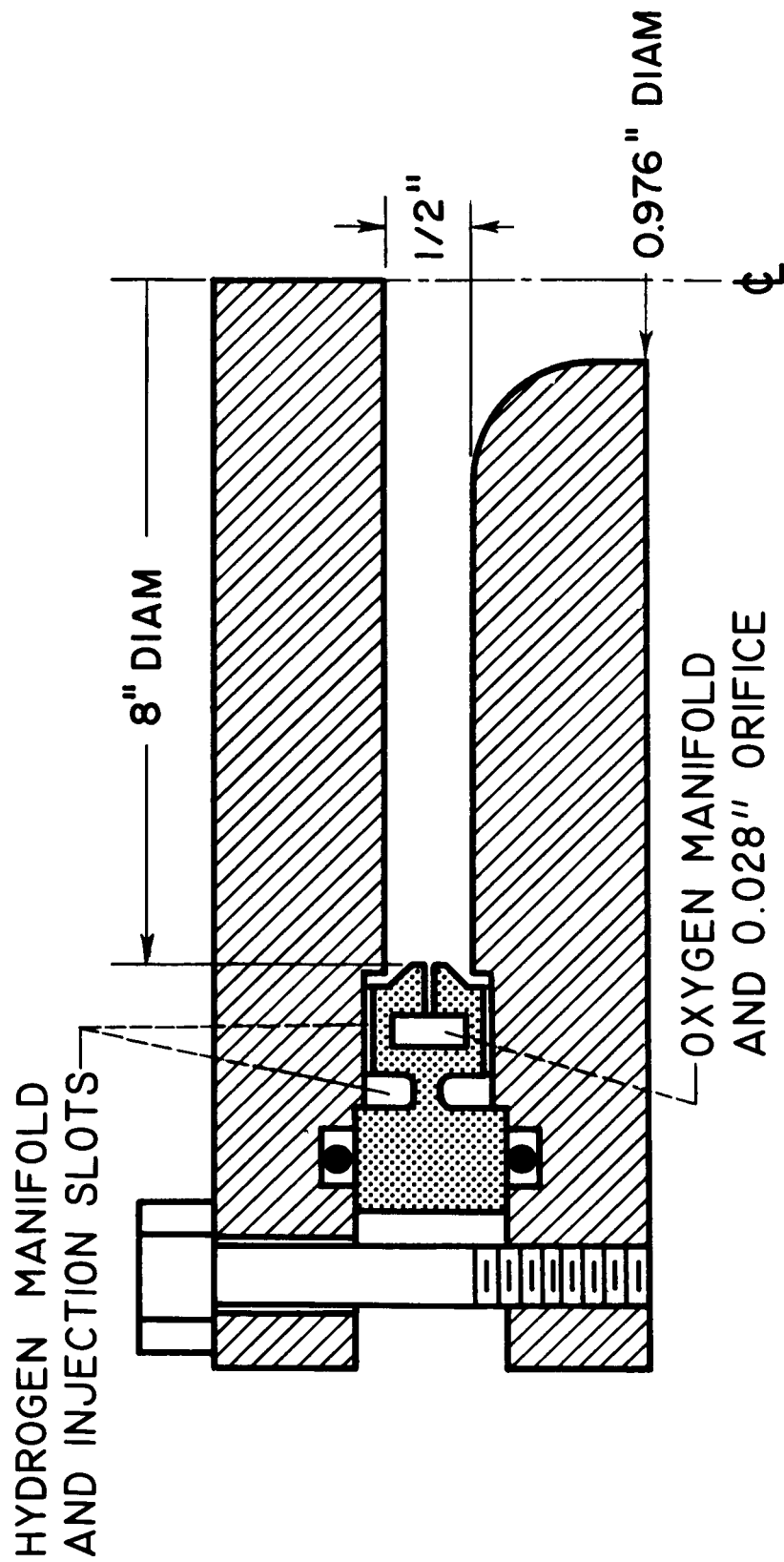
Attention: Mr. _____

Title _____



(a) ASSEMBLY.

FIGURE 1. - TWO-DIMENSIONAL CIRCULAR COMBUSTOR.



(b) CROSS SECTION.

FIGURE 1. - CONCLUDED. TWO-DIMENSIONAL CIRCULAR COMBUSTOR.

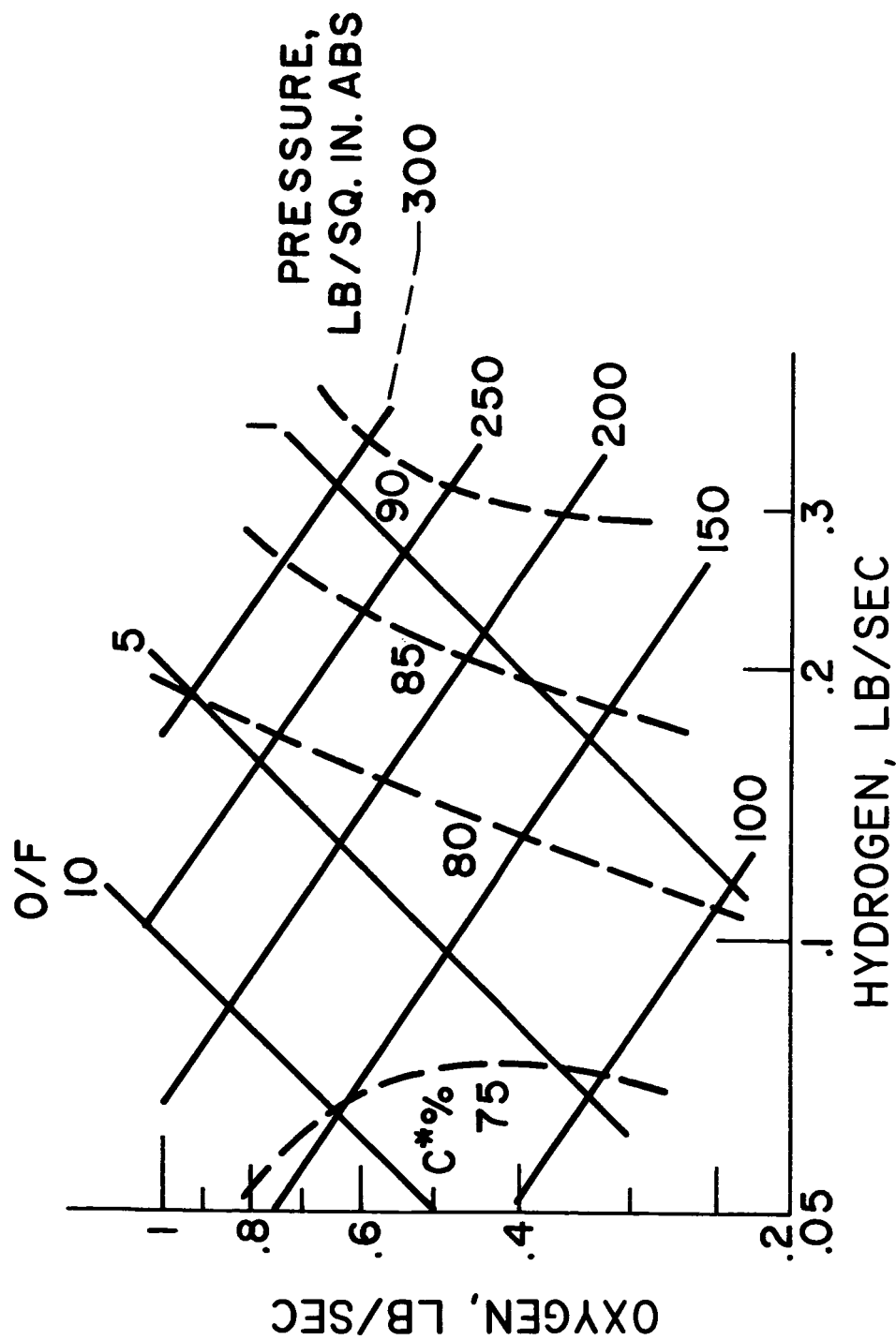


FIGURE 2. - COMBUSTOR PERFORMANCE.

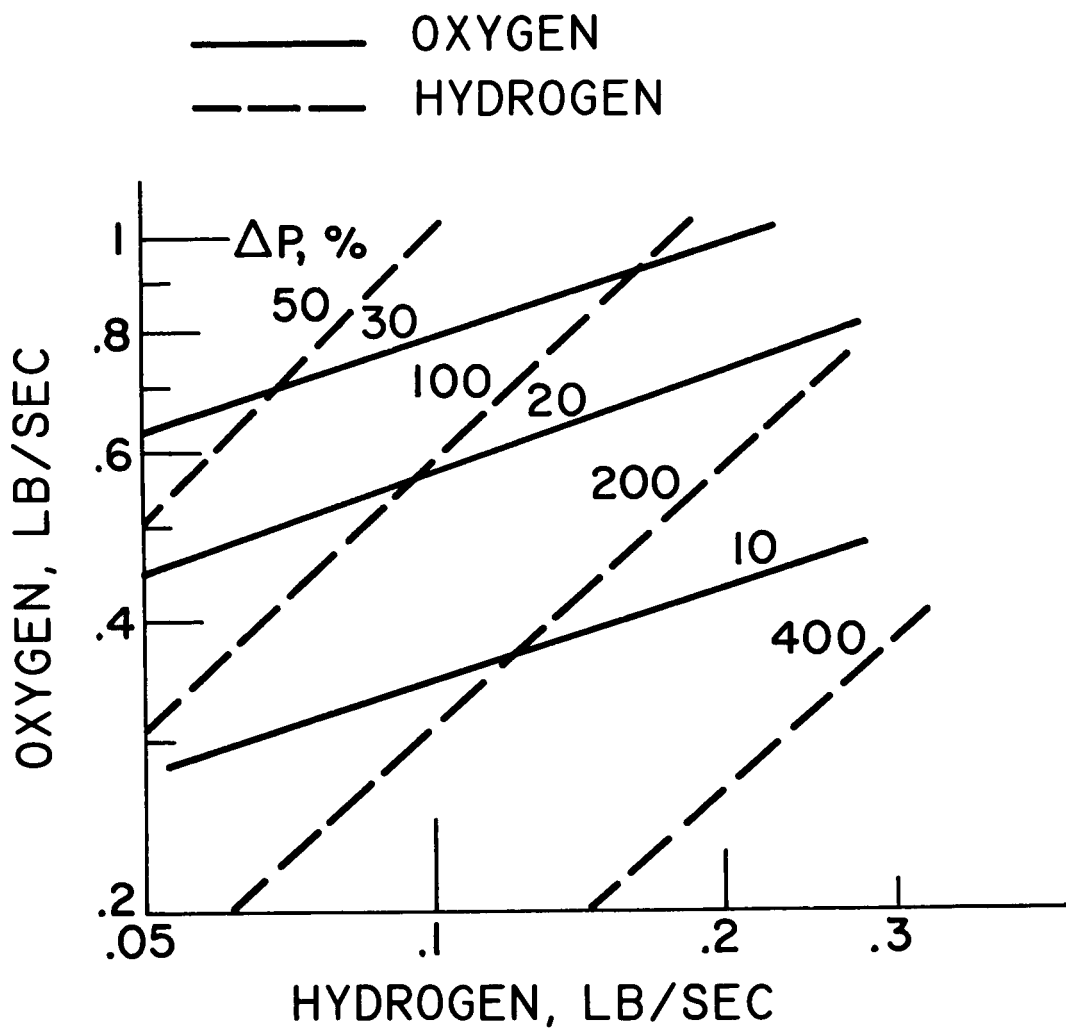


FIGURE 3. - INJECTION PRESSURE DROP IN PERCENT OF COMBUSTOR PRESSURE.



FIGURE 4. - TYPICAL OXYGEN JET
WITH STABLE COMBUSTION.

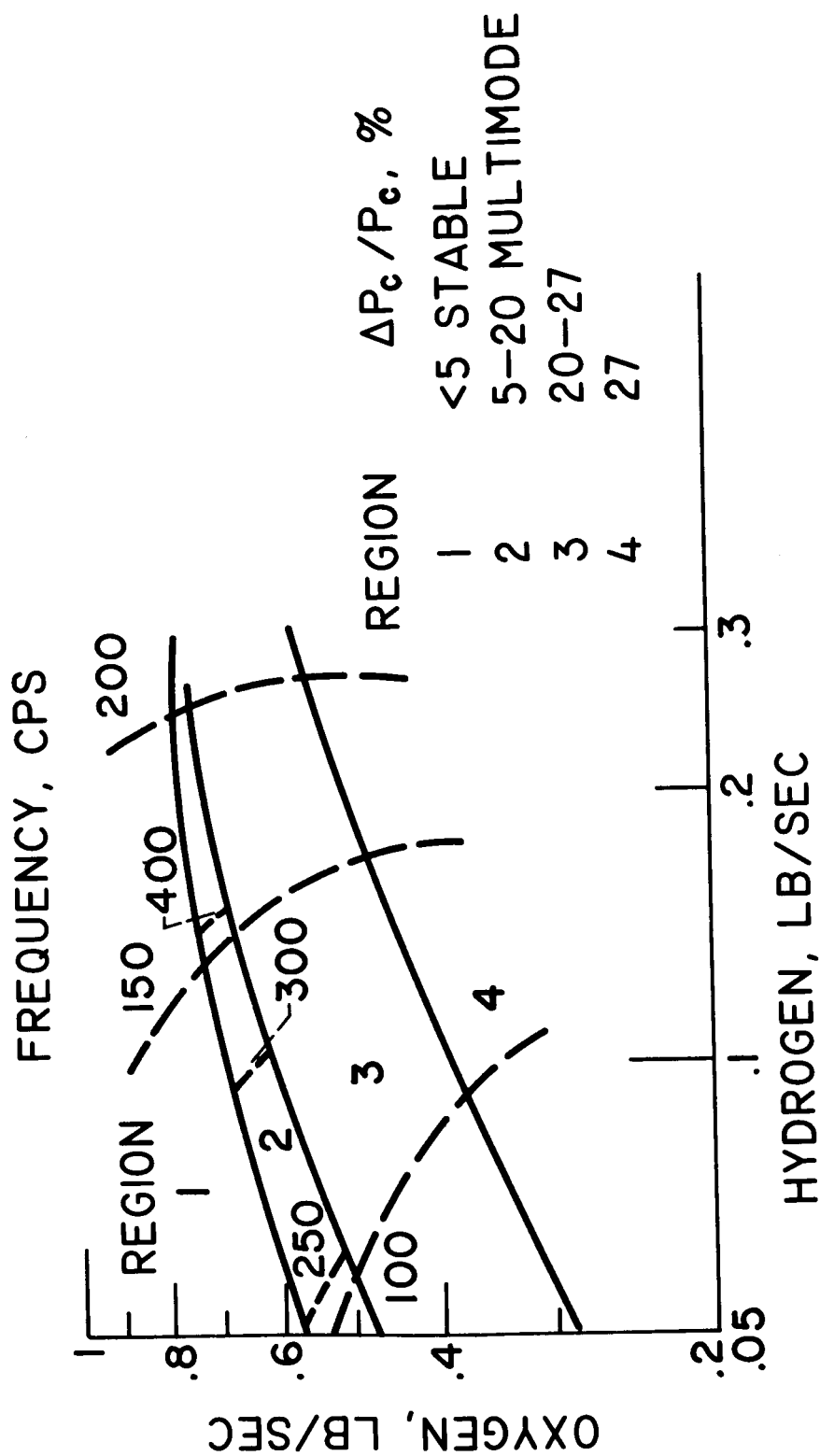


FIGURE 5. - CHUGGING INSTABILITY.

STABILITY
REGION

1

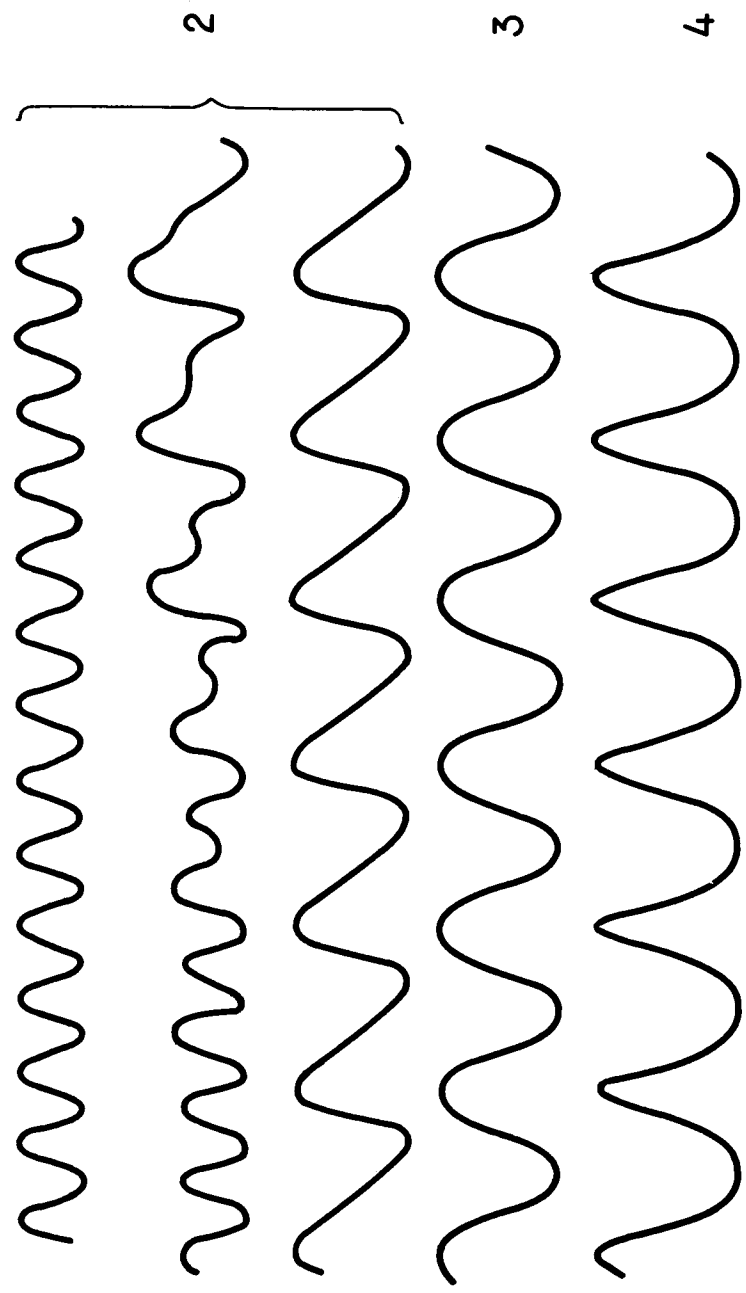
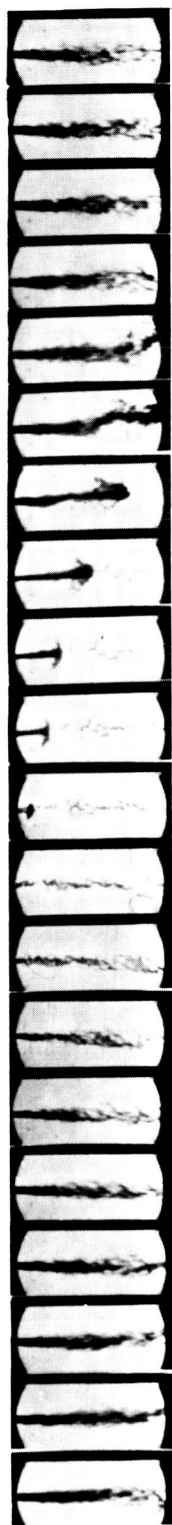
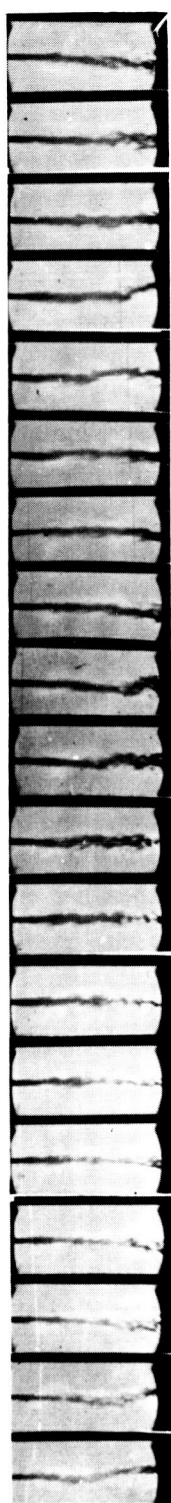


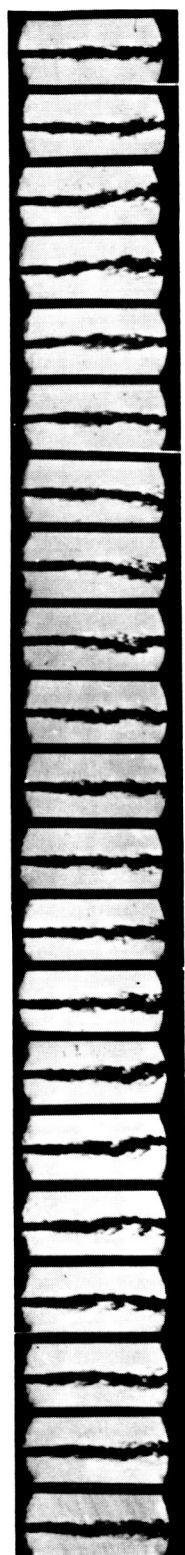
FIGURE 6. - TYPICAL WAVE SHAPE DURING CHUGGING INSTABILITY.



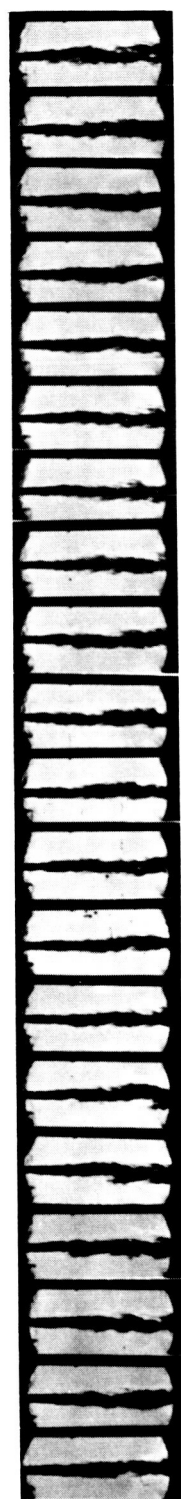
(a) REGION 1.



(b) REGION 2.

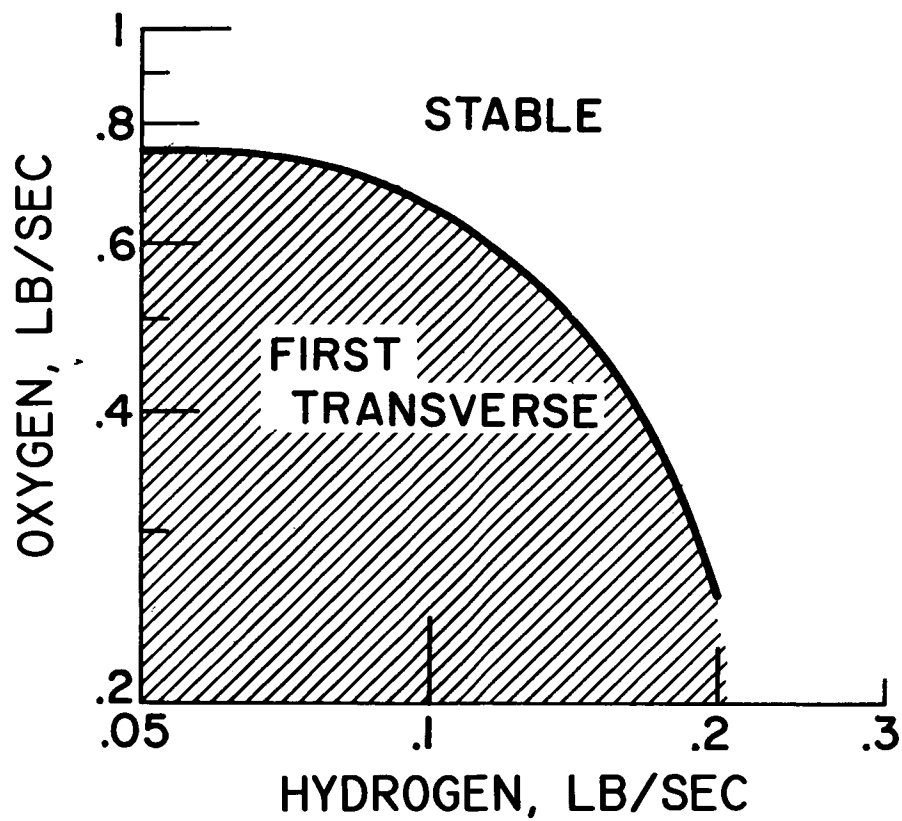


(c) REGION 3.



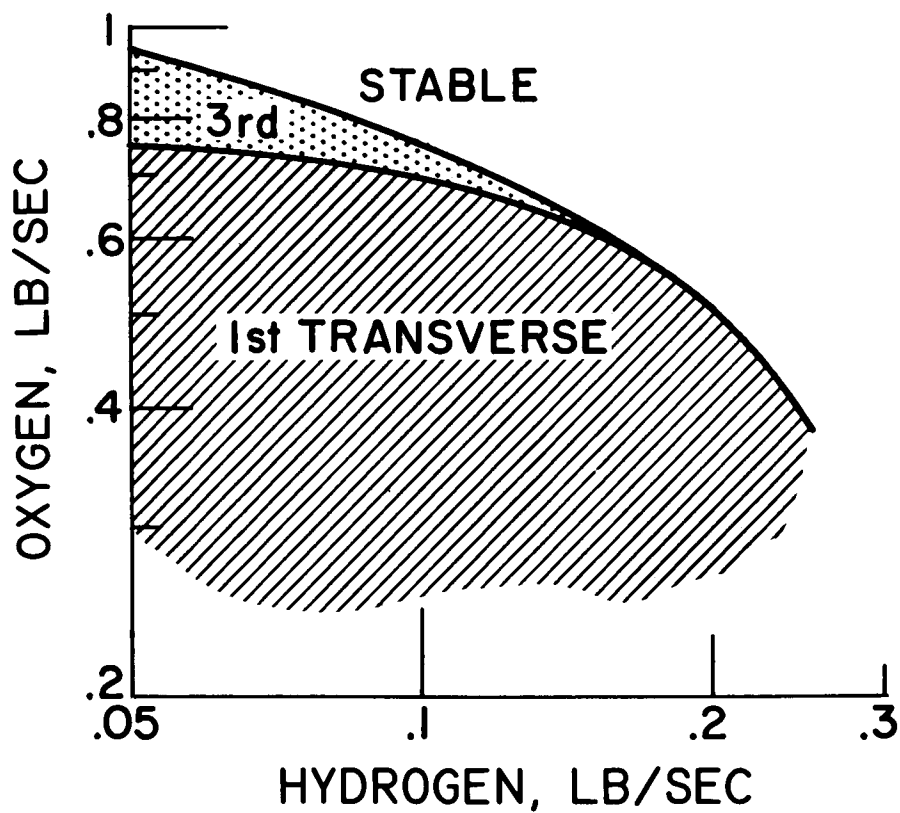
(d) REGION 4.

FIGURE 7. - LIQUID-OXYGEN JET BEHAVIOR WITH CHUGGING INSTABILITY.



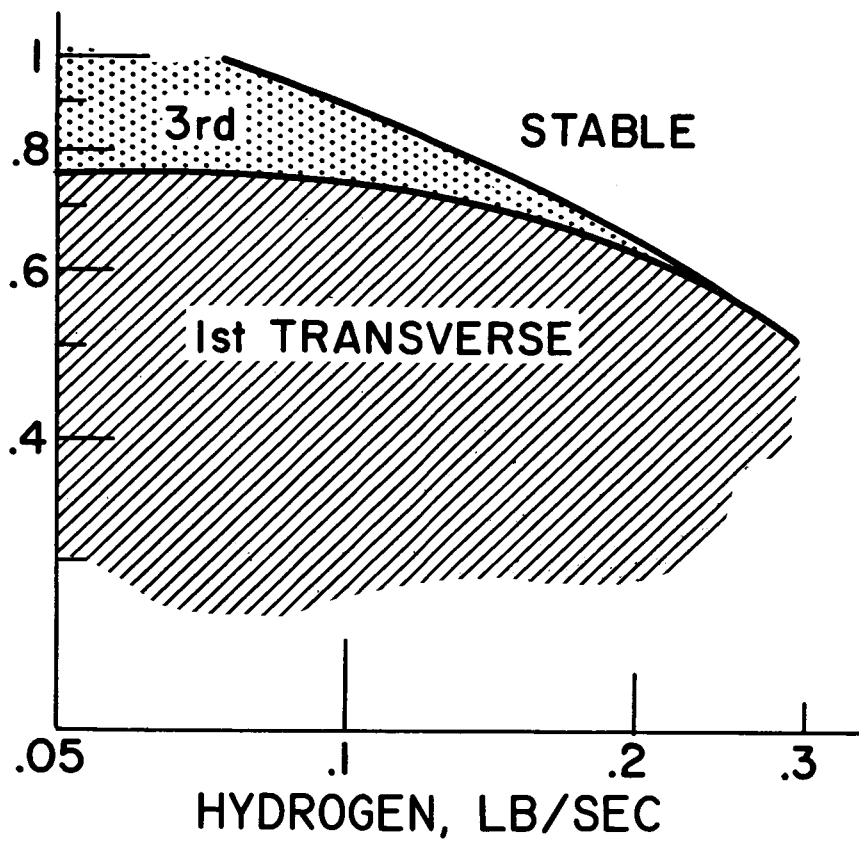
(a) NITROGEN FLOW, 0.029 LB/SEC.

FIGURE 8. - TRANSVERSE INSTABILITY REGIONS.



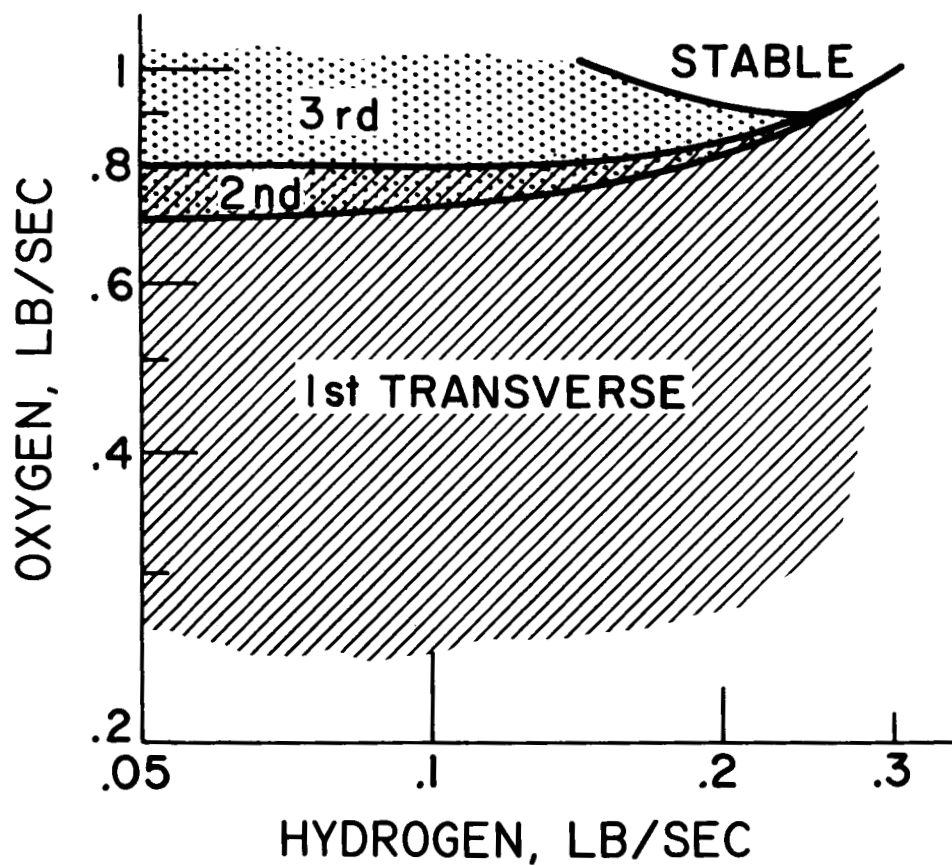
(b) NITROGEN FLOW, 0.55 LB/SEC.

FIGURE 8. - CONTINUED. TRANSVERSE
INSTABILITY REGIONS.



(c) NITROGEN FLOW, 0.112 LB/SEC.

FIGURE 8. - CONTINUED. TRANSVERSE
INSTABILITY REGIONS.



(d) NITROGEN FLOW, 0.222 LB/SEC.

FIGURE 8. - CONCLUDED. TRANSVERSE
INSTABILITY REGIONS.

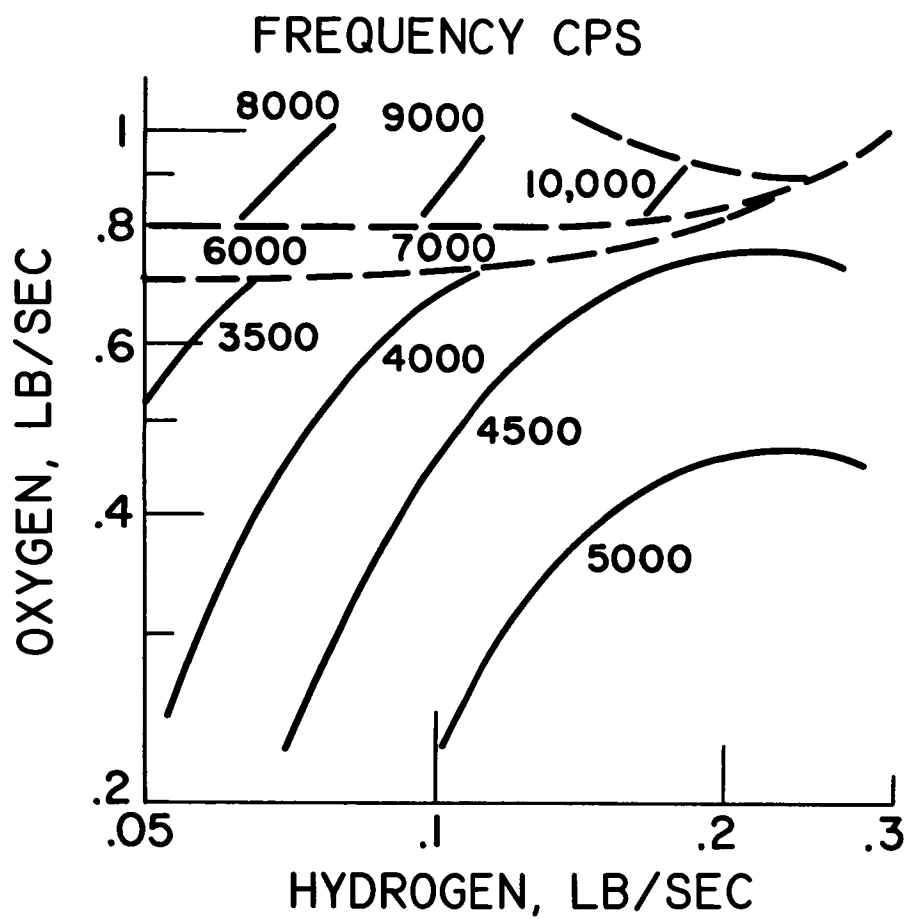


FIGURE 9. - FREQUENCY OF TRANSVERSE INSTABILITY WITH 0.222 LB/SEC NITROGEN FLOW.

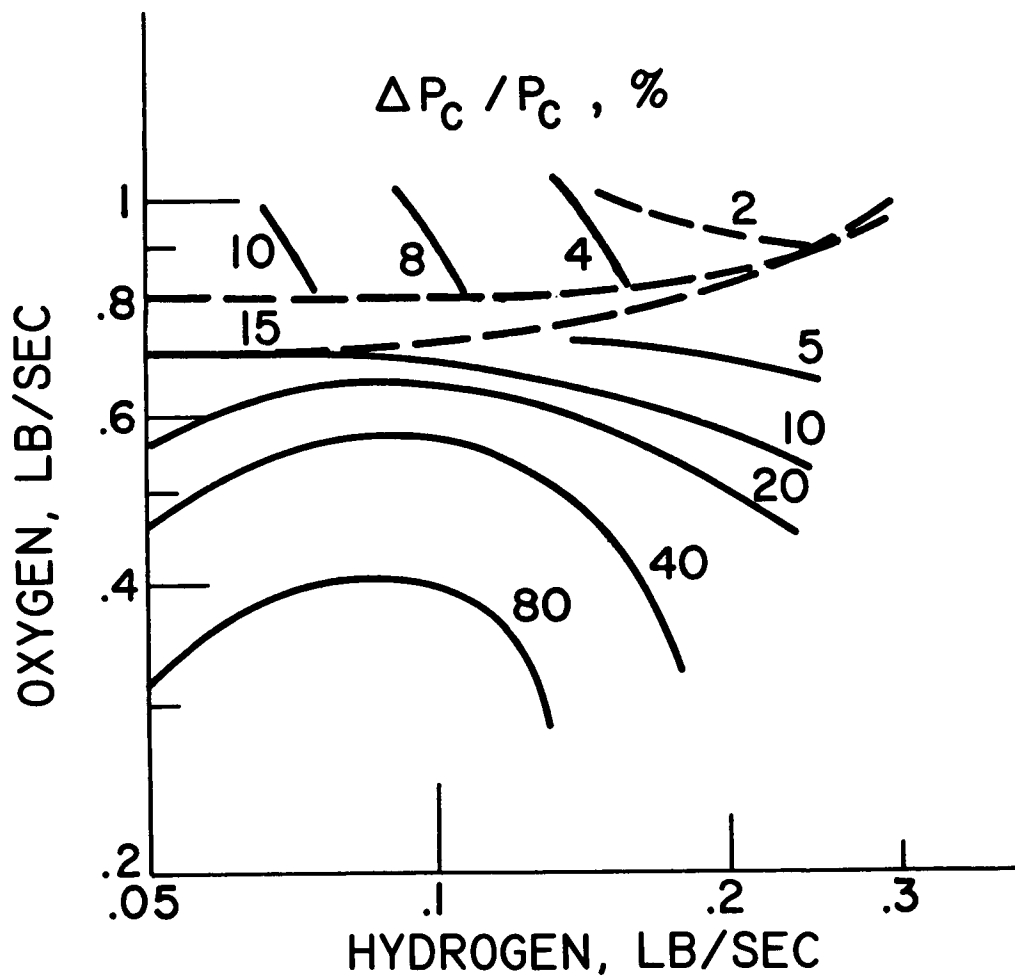


FIGURE 10. - AMPLITUDE OF TRANSVERSE INSTABILITY WITH 0.222 LB/SEC NITROGEN FLOW.

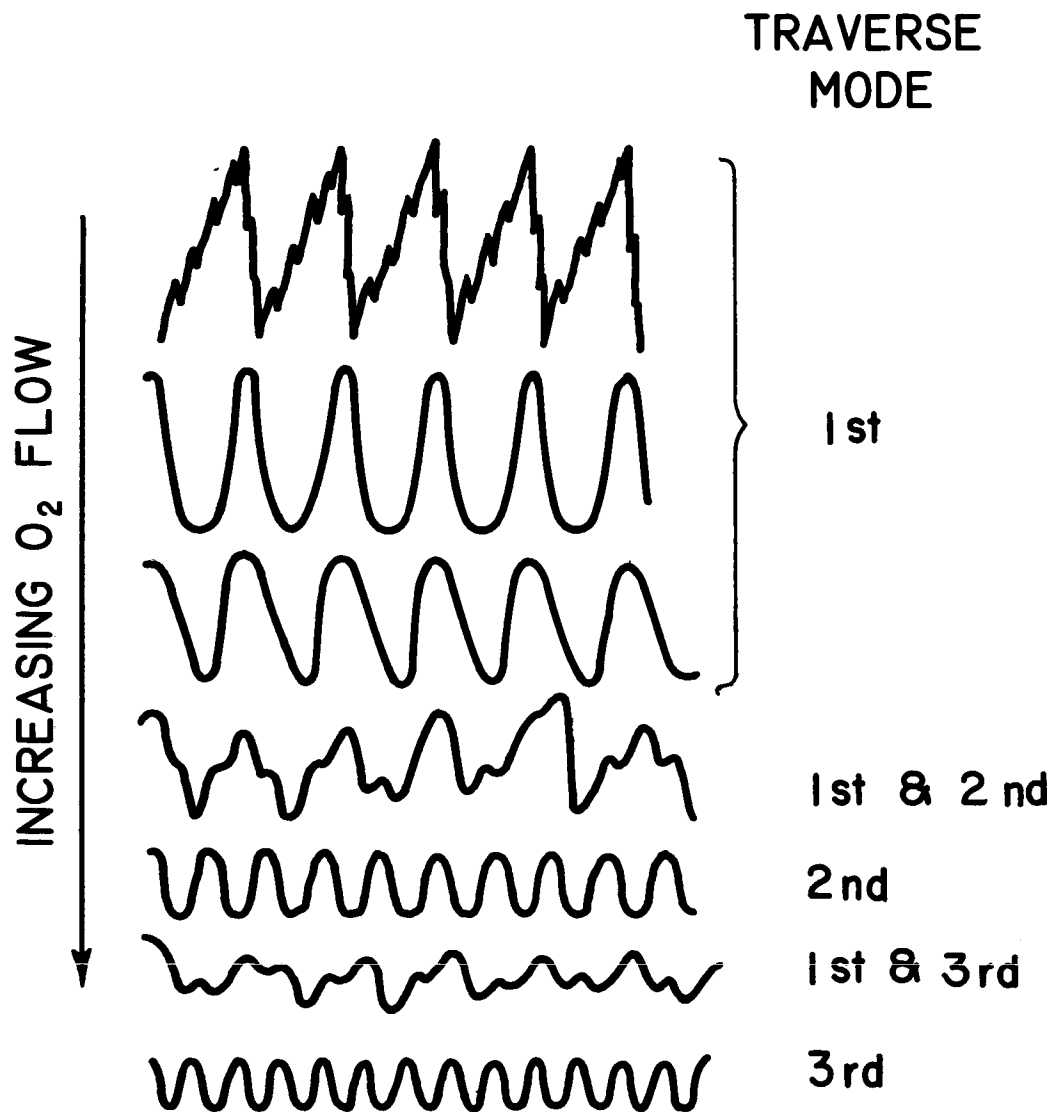
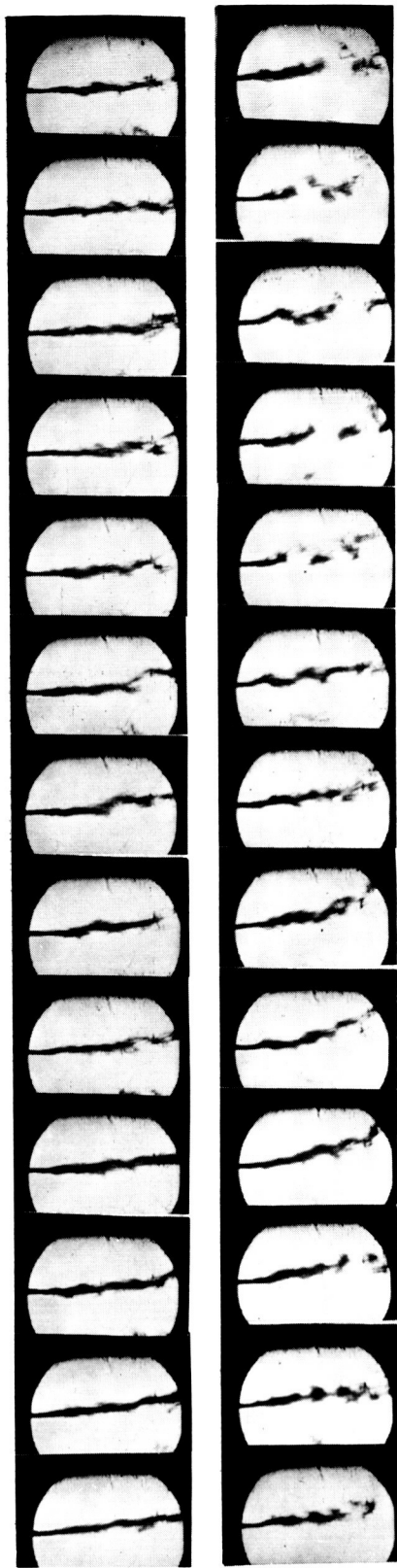
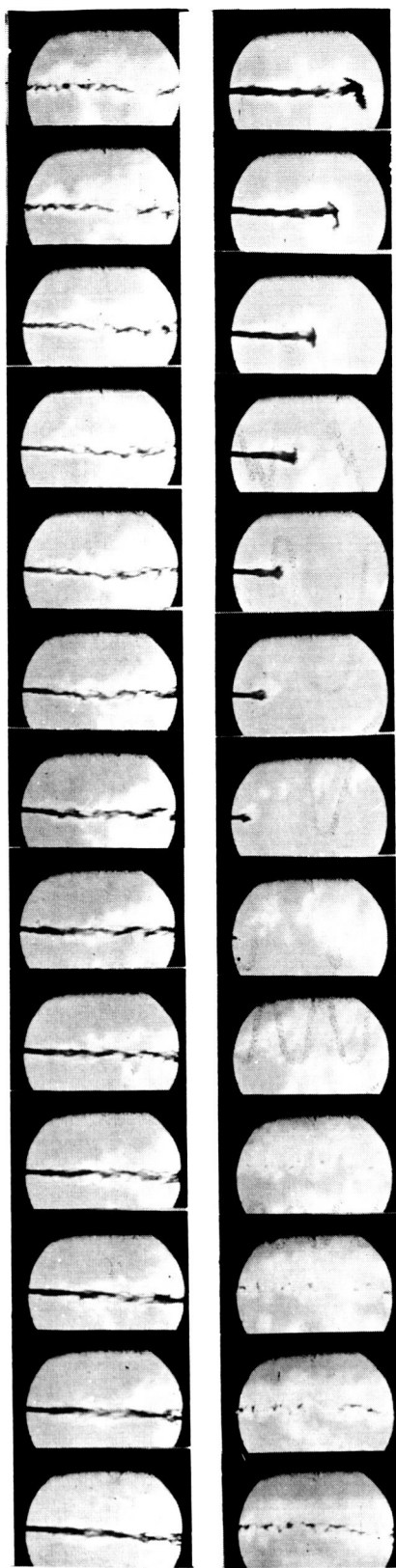


FIGURE 11. - P_c WAVE FORM; AT CONSTANT H_2 AND N_2 FLOW.

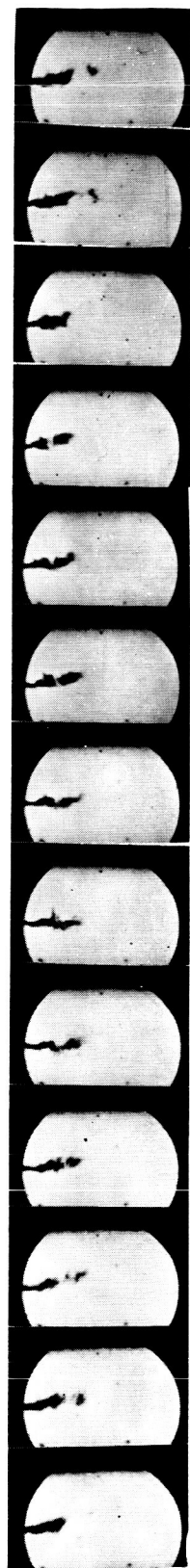


(a) TYPICAL TRANSITION.



(b) TRANSITION FOR LOW OXYGEN PRESSURE DROP.

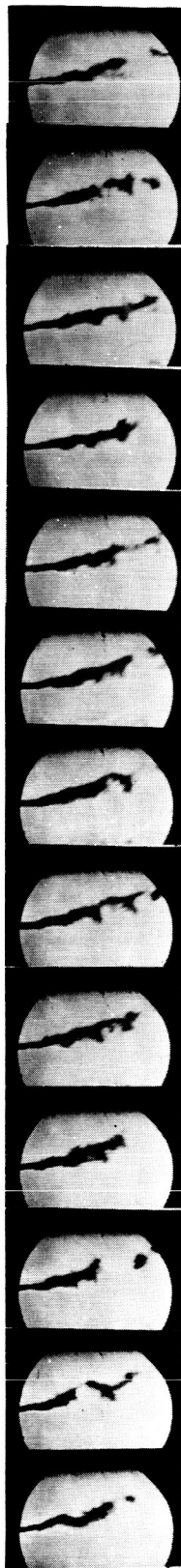
FIGURE 12. - TRANSITION FROM STABLE TO SCREAMING COMBUSTION.



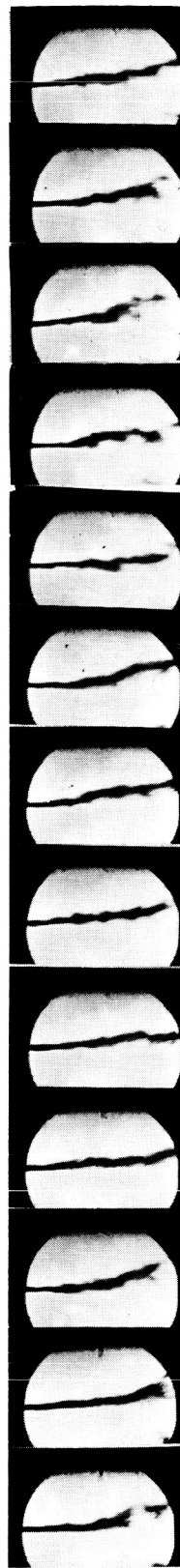
(a) $\Delta P_c / P_c > 0.40$; LOW OXYGEN JET VELOCITY.



(b) $\Delta P_c / P_c, 0.20-0.40$.



(c) $\Delta P_c / P_c, 0.10-0.20$.



(d) $\Delta P_c / P_c < 0.10$; HIGH OXYGEN JET VELOCITY.

FIGURE 13. - LIQUID-OXYGEN-JET BEHAVIOR WITH FIRST TRANSVERSE MODE OF INSTABILITY.